

EVALUATION OF n + Ca CROSS SECTIONS FOR THE ENERGY  
RANGE 1.0E-11 to 150 MeV

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This evaluation provides a complete representation of the nuclear data needed for transport, damage, heating, radioactivity, and shielding applications over the incident neutron energy range from 1.0E-11 to 150 MeV. The discussion here is divided into the region below and above 20 MeV.

INCIDENT NEUTRON ENERGIES < 20 MeV

Below 20 MeV the evaluation is based completely on the ENDF/B-VI.1 (Release 0) evaluation by C.Y.Fu AND D.M.Hetrick (Fu91).

INCIDENT NEUTRON ENERGIES > 20 MeV (40Ca calcs)

The ENDF/B-VI Release 3 evaluation extends to 40 MeV and includes cross sections and energy-angle data for all significant reactions. The present evauation utilizes a more compact composite reaction spectrum representation above 20 MeV in order to reduce the length of the file. No essential data for applications is lost with this representation. Additionally, we have modified the neutron reaction cross sections slightly to improve agreement with data above 20 MeV.

The evaluation above 20 MeV utilizes MF=6, MT=5 to represent all reaction data. Production cross sections and emission spectra are given for neutrons, protons, deuterons, tritons, alpha particles, gamma rays, and all residual nuclides produced ( $A>5$ ) in the reaction chains. To summarize, the ENDF sections with non-zero data above  $E_n = 20$  MeV are:

MF=3 MT= 1 Total Cross Section  
MT= 2 Elastic Scattering Cross Section  
MT= 3 Nonelastic Cross Section  
MT= 5 Sum of Binary (n,n') and (n,x) Reactions

MF=4 MT= 2 Elastic Angular Distributions

MF=6 MT= 5 Production Cross Sections and Energy-Angle Distributions for Emission Neutrons, Protons, Deuterons, and Alphas; and Angle-Integrated Spectra for Gamma Rays and Residual Nuclei That Are Stable Against Particle Emission

The evaluation is based on nuclear model calculations that have been benchmarked to experimental data. We use the GNASH code system (Yo92), which utilizes Hauser-Feshbach statistical, preequilibrium and direct-reaction theories. Spherical optical model calculations are used to obtain particle transmission coefficients for the Hauser-Feshbach calculations, as well as for the elastic neutron angular distributions.

Cross sections and spectra for producing individual residual nuclei are included for reactions that exceed a cross section of approximately 1 nb at any energy. The energy-angle-correlations for all outgoing particles are based on Kalbach systematics (Ka88).

A model was developed to calculate the energy distributions of all recoil nuclei in the GNASH calculations (Ch96a). The recoil energy distributions are represented in the laboratory system in MT=5, MF=6, and are given as isotropic in the lab system. All other data in MT=5, MF=6 are given in the center-of-mass system. This method of representation utilizes the LCT=3 option approved at the November, 1996, CSEWG meeting..

The starting point for this evaluation was the previous Livermore (1995) evaluation by Chadwick and Young for neutrons up to 100 MeV [Ch95], and protons up to 250 MeV [Ch96b]. The main additions in the current work were: (1) Extension of the neutron calculations to higher energies; (2) Inclusion of direct inelastic scattering to low-lying collective states using ECIS; (3) inclusion of a renormalization of the calculated results to circumvent a numerical inaccuracy at higher incident energies (>150 MeV) which ensure the individual reactions sum to the evaluated nonelastic cross section; (4) inclusion of A>4 nuclide production and nuclide energy spectra; (5) inclusion of triton emission; and (6) utilization of ENDF-6 format.

The neutron total cross section was evaluated from available experimental data. The evaluation was based primarily on Finlay's 1993 high-accuracy measurements [Fi93].

The optical potential of Islam [Is88] specially developed for n+Ca elastic scattering, was used for 20-60 MeV neutrons, and above this energy the Madland global potential was used [Ma88]. The Wilmore-Hodgson potential was used below 20 MeV [Wi64]. For incident protons, the Islam neutron potential was modified to account for proton scattering from 20 to 60 MeV, and again the Madland global potential was used at higher energies. The Becchetti-Greenlees potential was used for protons below 20 MeV [Be69]. For deuterons, tritons and alphas the method of Watanabe, which uses a modified Perey potential [Pe63], was applied at all energies [Ma88].

Direct inelastic scattering to the low-lying collective states was calculated with the ECIS code. Deformation lengths were taken from the works of Alarcon and Rapaport [8] and Honore et al. [Ho86], giving: 3- (Ex= 3.736 MeV, delta=1.340), 2+ (Ex=3.904, delta=0.360), and 5- (Ex=4.492, delta=0.930).

While the above optical potentials did describe the experimental neutron and proton nonelastic cross section data fairly well, we modified these theoretical predictions slightly to better agree with the measurements, and renormalized the transmission coefficients accordingly. The calculated neutron elastic scattering distributions agree well with experimental data.

Nuclear level densities were taken from the Ignatyuk model [Ig75], which includes a washing out of shell effects with increasing excitation energy, and gamma-ray strength functions were obtained from the model of Kopecky and Uhl [Ko90].

The existing ENDF/B-VI evaluation below 20 MeV was performed at Oak Ridge, for natural Calcium. Since 40Ca makes up approximately 97% of natural calcium, we have combined the natural evaluation below 20 MeV with our new 40Ca evaluation above 20 MeV. The combined evaluation up to 150 MeV can be treated as a natural evaluation to a good approximation. Using our 40Ca for natural Ca above 20 MeV is a very good approximation for transport and heating applications; although our evaluation above 20 MeV does omit the production of radionuclides with A>40 (the practical consequences of this are expected to be small).

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20000 = TARGET 1000Z+A (if A=0 then elemental)  
 1 = PROJECTILE 1000Z+A

## Nonelastic, elastic, and Production cross sections for A&lt;5 projectiles in barns:

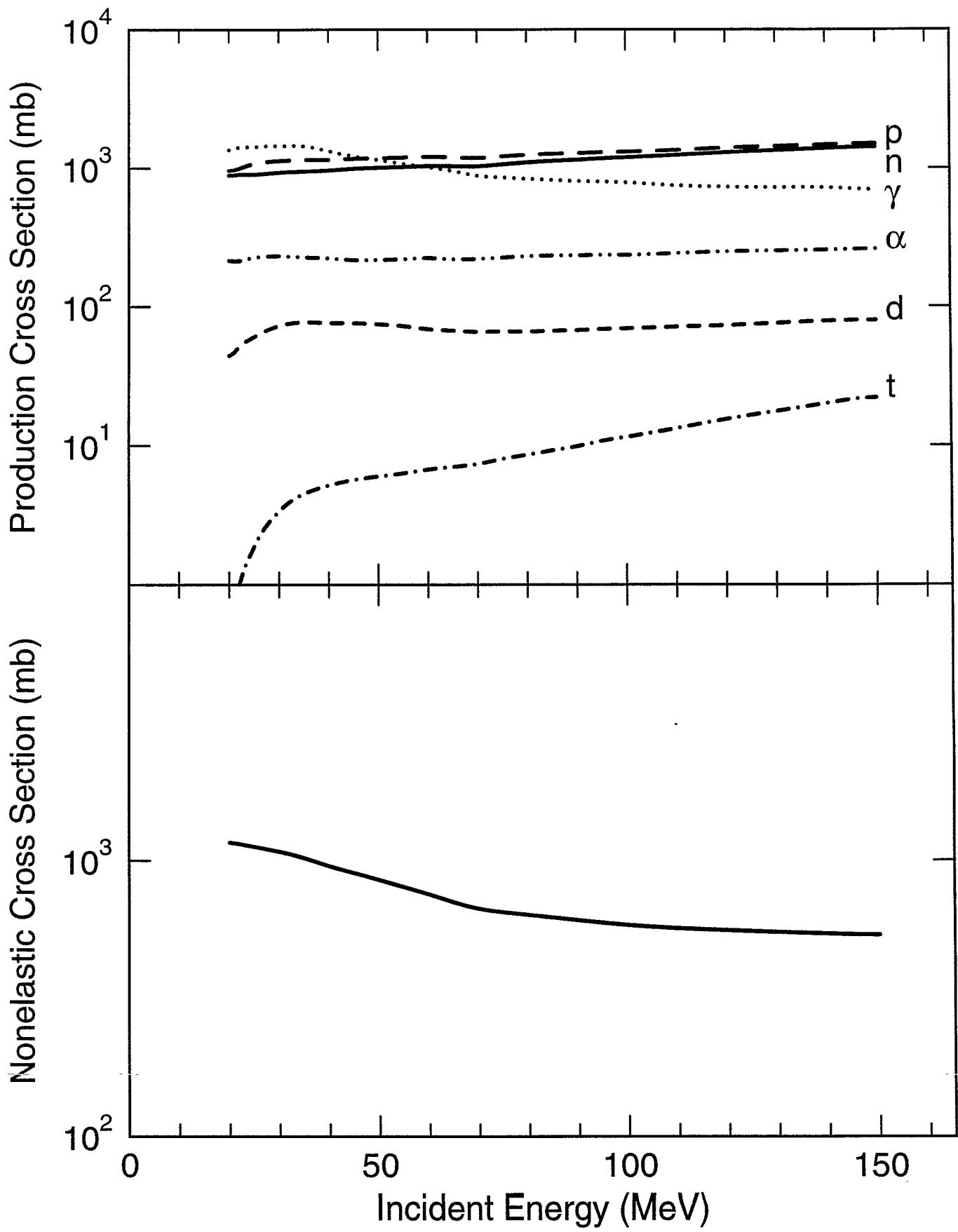
Energy	nonelas	elastic	neutron	proton	deuteron	triton	helium3	alpha	gamma
2.000E+01	1.162E+00	9.540E-01	8.871E-01	9.586E-01	4.428E-02	4.781E-04	0.000E+00	2.140E-01	1.355E+00
2.200E+01	1.148E+00	9.677E-01	8.982E-01	9.931E-01	5.158E-02	9.757E-04	0.000E+00	2.132E-01	1.416E+00
2.400E+01	1.131E+00	9.972E-01	8.979E-01	1.052E+00	5.787E-02	1.564E-03	0.000E+00	2.223E-01	1.423E+00
2.600E+01	1.112E+00	1.041E+00	9.041E-01	1.090E+00	6.338E-02	2.200E-03	0.000E+00	2.277E-01	1.434E+00
2.800E+01	1.094E+00	1.089E+00	9.170E-01	1.115E+00	6.861E-02	2.804E-03	0.000E+00	2.308E-01	1.451E+00
3.000E+01	1.075E+00	1.133E+00	9.298E-01	1.128E+00	7.270E-02	3.371E-03	0.000E+00	2.315E-01	1.451E+00
3.500E+01	1.019E+00	1.227E+00	9.479E-01	1.146E+00	7.723E-02	4.493E-03	0.000E+00	2.269E-01	1.446E+00
4.000E+01	9.530E-01	1.323E+00	9.658E-01	1.148E+00	7.622E-02	5.164E-03	0.000E+00	2.233E-01	1.332E+00
4.500E+01	8.995E-01	1.363E+00	9.941E-01	1.170E+00	7.596E-02	5.652E-03	0.000E+00	2.168E-01	1.220E+00
5.000E+01	8.490E-01	1.363E+00	1.011E+00	1.181E+00	7.453E-02	5.984E-03	0.000E+00	2.174E-01	1.146E+00
5.500E+01	8.000E-01	1.340E+00	1.024E+00	1.196E+00	7.233E-02	6.307E-03	0.000E+00	2.200E-01	1.077E+00
6.000E+01	7.520E-01	1.312E+00	1.037E+00	1.208E+00	6.874E-02	6.714E-03	0.000E+00	2.242E-01	1.017E+00
6.500E+01	7.043E-01	1.289E+00	1.035E+00	1.198E+00	6.694E-02	7.018E-03	0.000E+00	2.196E-01	9.567E-01
7.000E+01	6.680E-01	1.248E+00	1.034E+00	1.184E+00	6.557E-02	7.359E-03	0.000E+00	2.206E-01	8.826E-01
7.500E+01	6.483E-01	1.177E+00	1.066E+00	1.216E+00	6.613E-02	8.001E-03	0.000E+00	2.252E-01	8.560E-01
8.000E+01	6.340E-01	1.099E+00	1.098E+00	1.246E+00	6.583E-02	8.573E-03	0.000E+00	2.304E-01	8.365E-01
8.500E+01	6.198E-01	1.036E+00	1.127E+00	1.269E+00	6.667E-02	9.193E-03	0.000E+00	2.327E-01	8.192E-01
9.000E+01	6.060E-01	9.750E-01	1.148E+00	1.282E+00	6.729E-02	9.845E-03	0.000E+00	2.332E-01	8.056E-01
9.500E+01	5.930E-01	9.030E-01	1.174E+00	1.302E+00	6.854E-02	1.076E-02	0.000E+00	2.350E-01	7.977E-01
1.000E+02	5.820E-01	8.430E-01	1.195E+00	1.314E+00	6.935E-02	1.152E-02	0.000E+00	2.352E-01	7.862E-01
1.100E+02	5.669E-01	7.431E-01	1.242E+00	1.350E+00	7.123E-02	1.325E-02	0.000E+00	2.417E-01	7.495E-01
1.200E+02	5.570E-01	6.470E-01	1.297E+00	1.402E+00	7.292E-02	1.544E-02	0.000E+00	2.486E-01	7.320E-01
1.300E+02	5.487E-01	5.703E-01	1.344E+00	1.439E+00	7.555E-02	1.759E-02	0.000E+00	2.523E-01	7.244E-01
1.400E+02	5.420E-01	5.110E-01	1.392E+00	1.477E+00	7.840E-02	2.004E-02	0.000E+00	2.564E-01	7.233E-01
1.500E+02	5.372E-01	4.628E-01	1.425E+00	1.504E+00	7.946E-02	2.199E-02	0.000E+00	2.603E-01	6.994E-01

20000 = TARGET 1000Z+A (if A=0 then elemental)  
 1 = PROJECTILE 1000Z+A

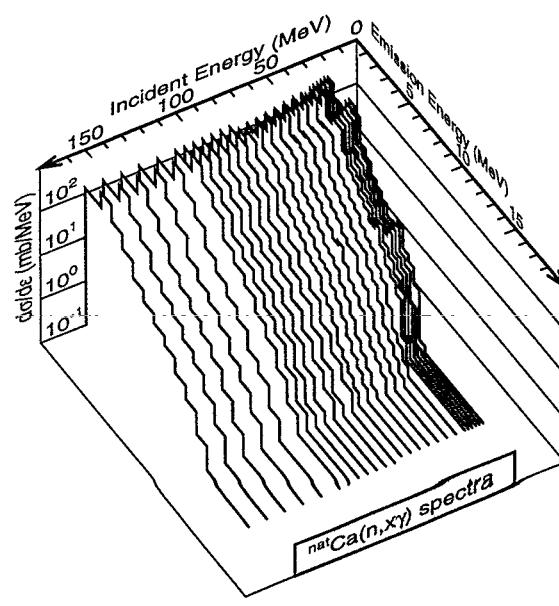
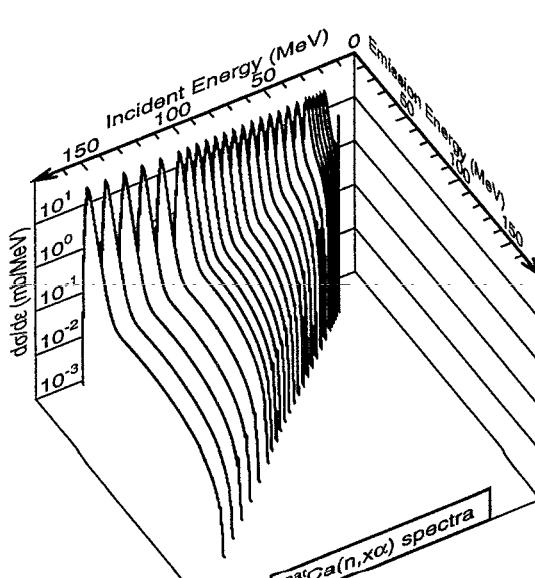
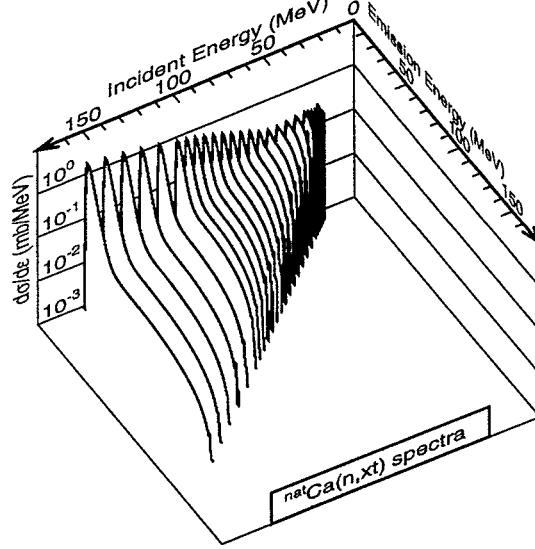
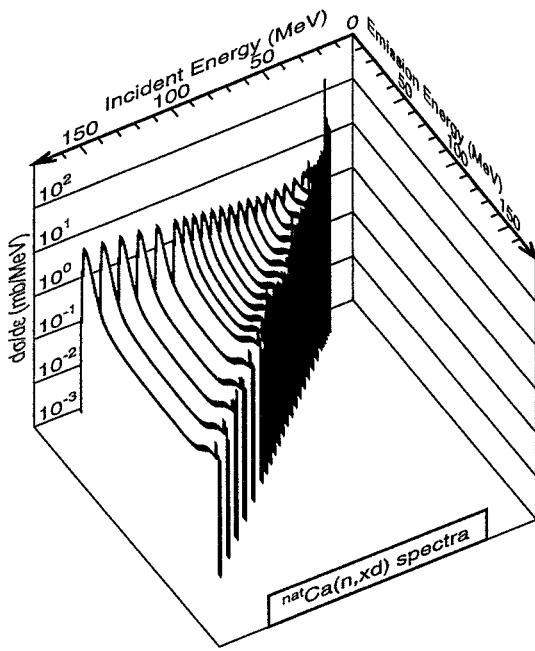
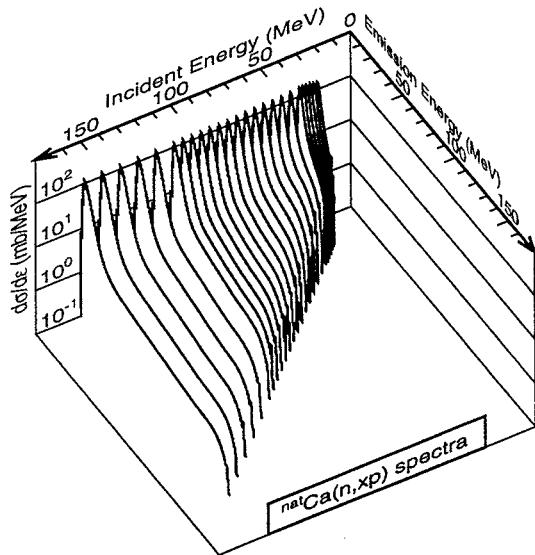
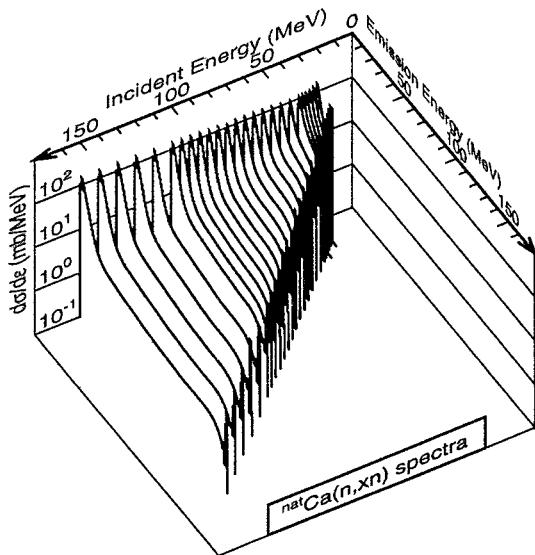
## Kerma coefficients in units of f.Gy.m^2:

Energy	proton	deuteron	triton	helium3	alpha	non-rec	elas-rec	TOTAL
2.000E+01	1.163E+00	9.359E-02	5.499E-04	0.000E+00	4.235E-01	1.996E-01	5.635E-02	1.936E+00
2.200E+01	1.251E+00	1.227E-01	1.307E-03	0.000E+00	4.299E-01	2.101E-01	4.706E-02	2.062E+00
2.400E+01	1.376E+00	1.521E-01	2.405E-03	0.000E+00	4.531E-01	2.216E-01	4.631E-02	2.251E+00
2.600E+01	1.475E+00	1.817E-01	3.833E-03	0.000E+00	4.698E-01	2.305E-01	4.585E-02	2.407E+00
2.800E+01	1.573E+00	2.142E-01	5.460E-03	0.000E+00	4.841E-01	2.373E-01	4.543E-02	2.559E+00
3.000E+01	1.678E+00	2.461E-01	7.234E-03	0.000E+00	4.925E-01	2.436E-01	4.480E-02	2.712E+00
3.500E+01	1.914E+00	3.125E-01	1.178E-02	0.000E+00	4.990E-01	2.572E-01	4.309E-02	3.038E+00
4.000E+01	2.114E+00	3.584E-01	1.576E-02	0.000E+00	5.024E-01	2.623E-01	4.229E-02	3.295E+00
4.500E+01	2.331E+00	4.104E-01	1.968E-02	0.000E+00	5.003E-01	2.674E-01	4.056E-02	3.569E+00
5.000E+01	2.519E+00	4.505E-01	2.321E-02	0.000E+00	5.120E-01	2.714E-01	3.844E-02	3.814E+00
5.500E+01	2.690E+00	4.778E-01	2.637E-02	0.000E+00	5.265E-01	2.742E-01	3.640E-02	4.031E+00
6.000E+01	2.830E+00	4.756E-01	2.907E-02	0.000E+00	5.422E-01	2.754E-01	3.476E-02	4.187E+00
6.500E+01	2.936E+00	4.943E-01	3.166E-02	0.000E+00	5.406E-01	2.726E-01	3.305E-02	4.309E+00
7.000E+01	3.053E+00	5.111E-01	3.424E-02	0.000E+00	5.495E-01	2.719E-01	3.093E-02	4.451E+00
7.500E+01	3.244E+00	5.334E-01	3.701E-02	0.000E+00	5.669E-01	2.772E-01	2.837E-02	4.687E+00
8.000E+01	3.454E+00	5.427E-01	3.972E-02	0.000E+00	5.848E-01	2.819E-01	2.593E-02	4.929E+00
8.500E+01	3.655E+00	5.691E-01	4.238E-02	0.000E+00	5.997E-01	2.850E-01	2.402E-02	5.175E+00
9.000E+01	3.840E+00	5.921E-01	4.485E-02	0.000E+00	6.079E-01	2.874E-01	2.227E-02	5.394E+00
9.500E+01	4.027E+00	6.115E-01	4.780E-02	0.000E+00	6.221E-01	2.909E-01	2.039E-02	5.620E+00
1.000E+02	4.206E+00	6.323E-01	5.050E-02	0.000E+00	6.314E-01	2.926E-01	1.884E-02	5.831E+00
1.100E+02	4.612E+00	6.664E-01	5.607E-02	0.000E+00	6.602E-01	2.990E-01	1.636E-02	6.310E+00
1.200E+02	5.056E+00	6.627E-01	6.253E-02	0.000E+00	6.912E-01	3.061E-01	1.408E-02	6.793E+00
1.300E+02	5.490E+00	6.860E-01	6.870E-02	0.000E+00	7.163E-01	3.213E-01	1.230E-02	7.295E+00
1.400E+02	5.922E+00	6.969E-01	7.542E-02	0.000E+00	7.434E-01	3.380E-01	1.092E-02	7.786E+00
1.500E+02	6.378E+00	6.856E-01	8.122E-02	0.000E+00	7.654E-01	3.508E-01	9.812E-03	8.271E+00

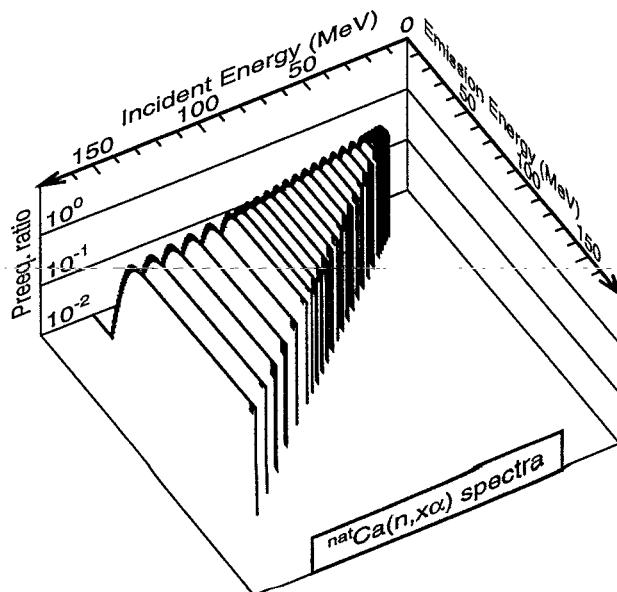
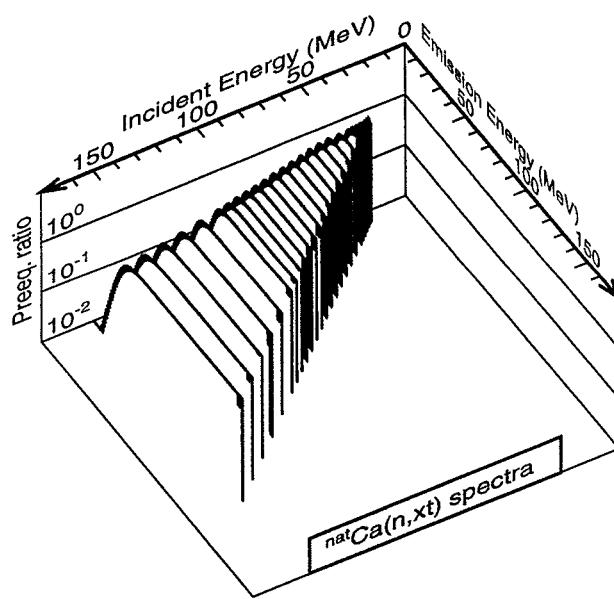
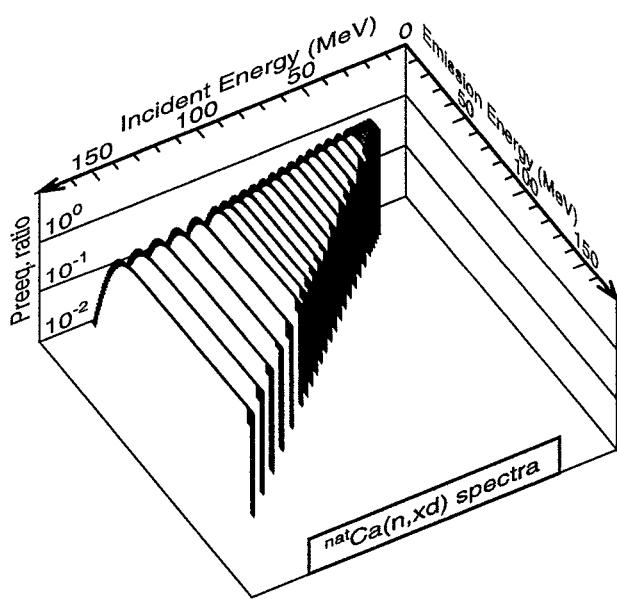
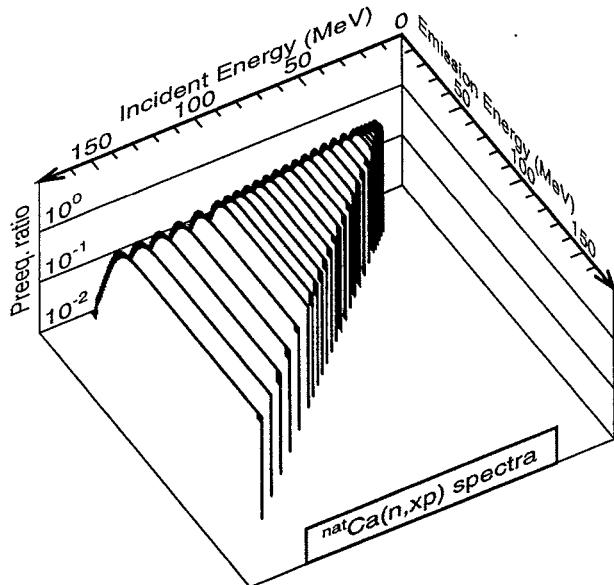
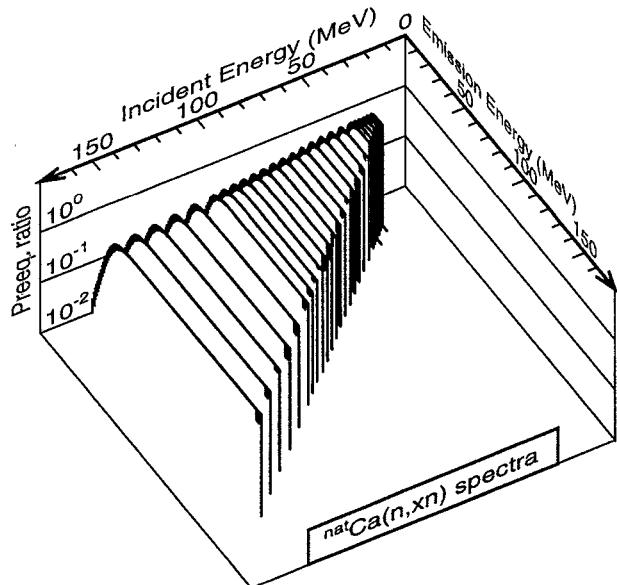
$n + ^{nat}Ca$  nonelastic and production cross sections



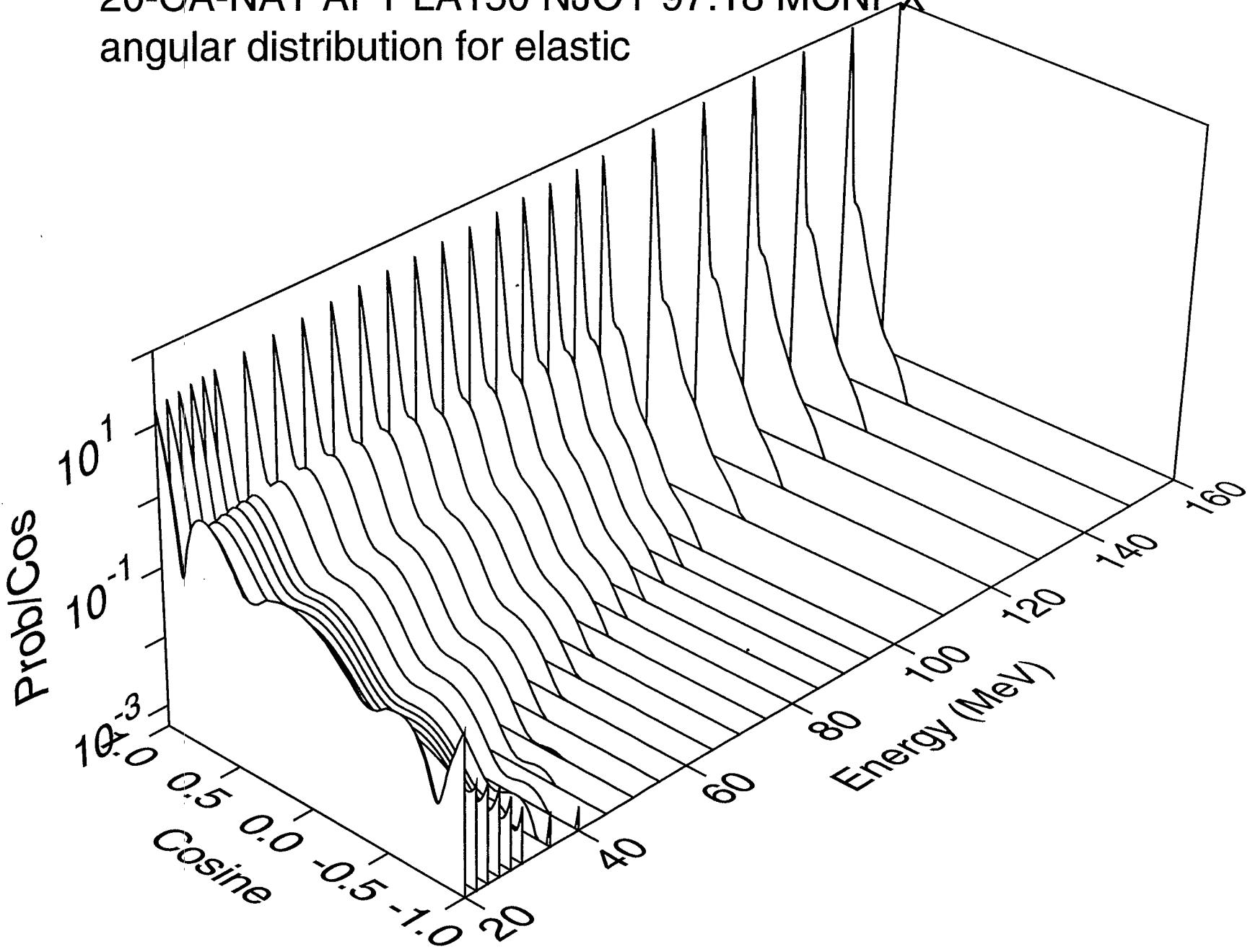
# $n + ^{nat}\text{Ca}$ angle-integrated emission spectra



# $n + ^{nat}\text{Ca}$ Kalbach preequilibrium ratios

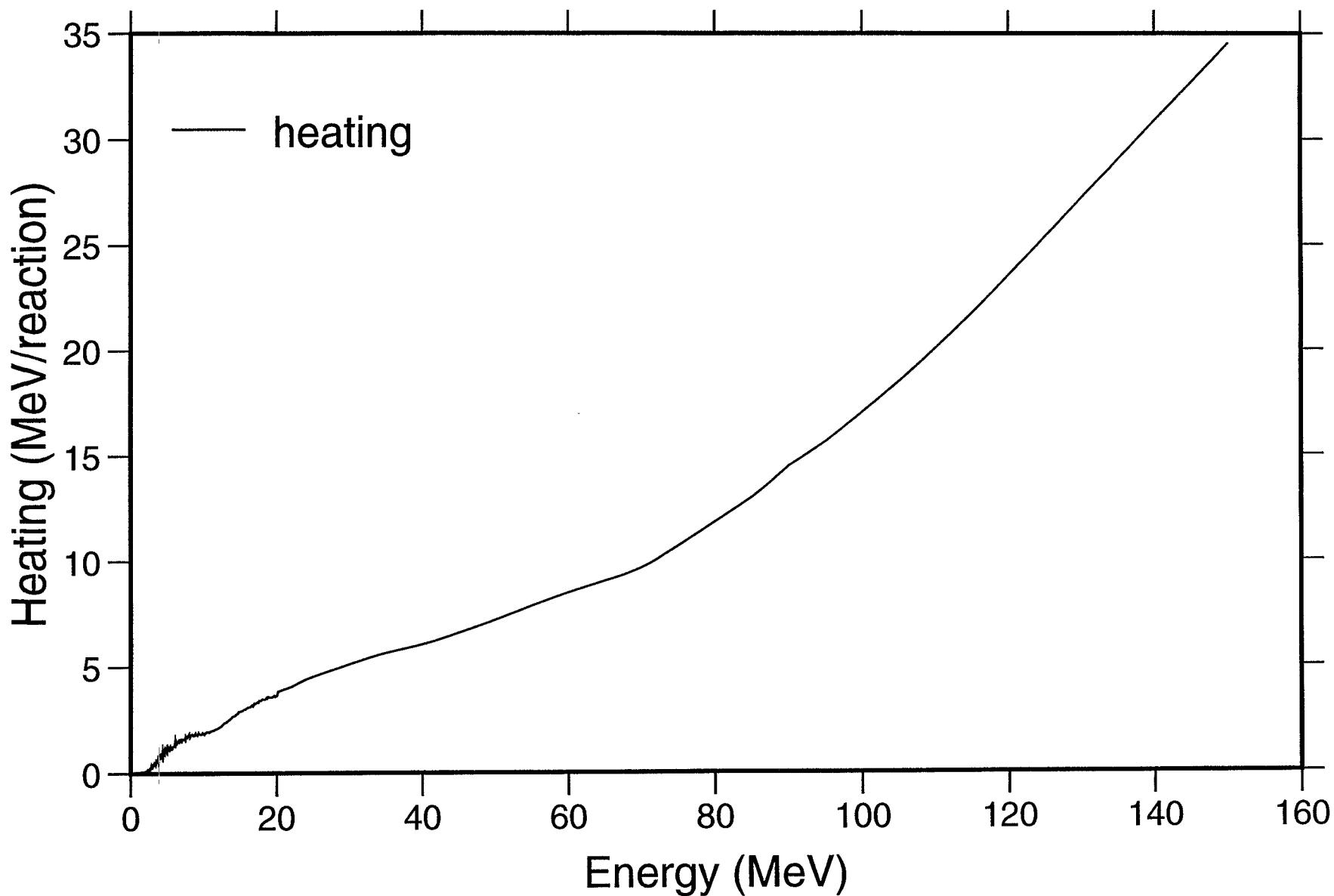


20-CA-NAT APT LA150 NJOY 97.18 MCNPX  
angular distribution for elastic



20-CA-NAT APT LA150 NJOY 97.18 MCNPX

Heating



20-CA-NAT APT LA150 NJOY 97.18 MCNPX

## Damage

